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Optimizing genotype-environment-management interactions to enhance productivity and eco-efficiency for wheat-maize rotation in the North China Plain

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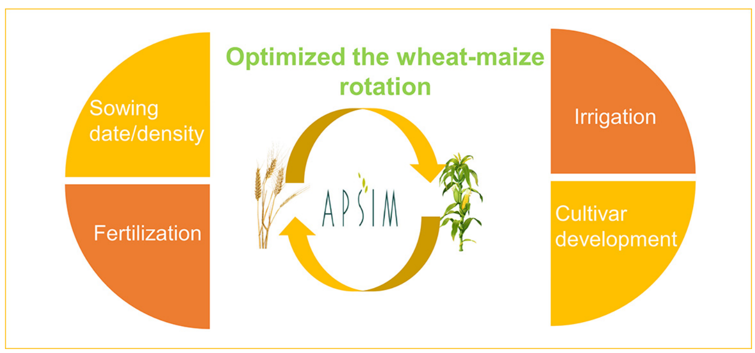
HIGHLIGHTS

- The Genotype (G) × Environment (E) × Management (M) interactions were optimized.
- The optimal sowing date and density were determined to maintain high yield.
- The optimal irrigation and nitrogen application rates were determined.
- Desirable maize cultivars traits include long growth period and high grain filling rate.
- Wheat cultivars with medium vernalization sensitivity and high grain filling rate were desirable.

GRAPHICAL ABSTRACT



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ABSTRACT

Agricultural production is facing unprecedented challenges to ensure food security by increasing productivity and in the meantime lowering environmental risk, especially in China. To enhance productivity and eco-efficiency of the typical winter wheat-summer maize rotation simultaneously in the North China Plain (NCP), we optimized the Genotype (G) × Environment (E) × Management (M) interactions to propose the optimal agronomic management practices and cultivars for four representative sites, with the Agricultural Production Systems sIMulator (APSIM) model and detailed field trial data. The results showed that an appropriate delay in sowing date could mitigate climatic negative effects and a proper increase in sowing density could increase yield. The optimal nitrogen application rate could be 180 kg N ha^{-1} year^{-1} for maize. For the cropping system, 240 mm of irrigation for wheat and 330–390 kg N ha^{-1} year^{-1} of nitrogen application rate (150–210 kg N ha^{-1} year^{-1} for wheat and 180 kg N ha^{-1} year^{-1} for maize) were suitable to sustain high yield, resource use efficiency, and lower N_2O emissions. These recommended levels were, respectively, 40% less than the current irrigation and N application rate commonly used by local farmers. The recommended management practices could increase groundwater recharge while reducing nitrogen leaching and N_2O emissions without reducing yield. The maize cultivars with a long growth duration, large grain number and grain-filling rate are desirable. The desirable wheat cultivars are characterized with a medium vernalization sensitivity and high grain filling rate. The present study demonstrated an

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effective approach to develop sustainable intensification options for producing more with less environmental costs through optimizing G × E × M interactions.

1. Introduction

Global food demand is increasing with population growth and dietary change (Kastner et al., 2012). However, food security is facing challenges from increasing external inputs, cultivated land reduction, water shortage and climate change (Xiong et al., 2014; Knox et al., 2016). Wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) are two staple crops in China. The North China Plain (NCP) is one of the primary crop production areas in China, where the typical winter wheat-summer maize rotation accounts for about 70% of the total arable land (Li et al., 2016). The total production in the NCP accounts for approximately half and one third of the national wheat and maize production, respectively (Liang et al., 2011). Crop yields have been increasing for the recent several decades under the combination of crop cultivar development, climate change, and improved agronomic managements (Qin et al., 2015; Bai et al., 2016). Meanwhile, environmental pollution caused by farmers' unreasonable managements has become a thorny problem (Zhao et al., 2015). Sustainable intensification of agricultural systems for enhancing productivity and ecological benefits simultaneously is of the essence to cope with the growing demand for food in the future.

Agricultural sustainable intensification needs to optimize the Genotype (G) × Environment (E) × Management (M) interactions for a target environment. Firstly, different sowing dates affect crop growth and yield, so shift of sowing date is an effective practice for crop to cope with climate risk (Tao et al., 2012). Sowing density is also an important agronomic management practice impacting grain yield notably. Holliday (1960) has demonstrated that the relationship between crop yield and sowing density is parabolic. Low sowing density results in low yield because of the limited ears per unit area, while an appropriately high sowing density could produce more because there were more and larger ears per unit area. However, too high sowing density could lead to grain yield reduction due to intensified competition for resources (Sangoi et al., 2002). The optimal sowing density is of difference under various planting patterns or locations. Therefore, determination of the optimal sowing density is another agronomic management goal especially for the regions where environmental resources is limited (Ren et al., 2016) like the NCP.

In the past decades, excessive application of nitrogen (N) fertilizer is very common in the double cropping system in the NCP, which led to massive environmental N loss and subsequent negative impacts (Liu et al., 2013). The average N fertilizer inputs are as high as 600 kg N ha^{-1} yr^{-1} (Zhong et al., 2006) but only <30% of the fertilizer N applied is taken up by crops (Zhang et al., 2008). The large amount of N loss by denitrification and N leaching leads to pollution and depletion of groundwater or soil and increase of greenhouse gas (GHG) emissions, especially N_2O (Ju et al., 2009; Zhang et al., 2014; Li et al., 2016). Additionally, water resource shortage is one major factor limiting crop growth and yield formation in arid or semiarid agricultural area (Zhao et al., 2018). The NCP is a typical semiarid area. Thus, it is vital to increase crop yield per unit water on per unit land. However, approximately 400–450 mm of irrigation water is applied annually in the wheat-maize cropping system (Zhang et al., 2006), resulting in much drainage, N loss, and low economic return (Fang et al., 2013; Zhao et al., 2015). Groundwater overuse is not controlled and the increasing of irrigation water has accelerated the decline of the groundwater table (Zhang et al., 2006). The high inputs of N fertilizer and irrigation water have increased N_2O emissions (Zhang et al., 2014), however the N_2O emissions from agro-ecosystem are seldom considered together with crop productivity. Optimizing agronomic management practices to increase water/nitrogen use efficiency and reduce N_2O emissions simultaneously is an effective way to increase crop yield with less associated environmental costs (Chen et al., 2014). Besides water and nitrogen inputs, selection of suitable cultivars for a specific environment is essential, which can substantially increase crop productivity and resource use efficiency. Crop cultivar development has contributed greatly to yield increase in the past decades (Gao et al., 2017), compensating the adverse impact of climate change.

The overall goal of this study is to explore sustainable intensification options to increase crop yield and eco-efficiency for the wheat-maize rotation in the NCP, by optimizing the Genotype (G) × Environment (E) × Management (M) interactions. Many previous studies addressed the single issue separately, but this study tried to come up with a full set of optimal agronomic management practices and cultivars for the cropping system in terms of sowing date, sowing density, irrigation, nitrogen application rate, and crop cultivar. We used the Agricultural Production Systems sIMulator (APSIM) wheat-maize rotation model, together with the field trial data from 1981 to 2009, to investigate the yield, resource (water/N) use efficiency, and N_2O emissions of the wheat-maize rotation, at four representative agro-meteorological experiment stations in the NCP. The objectives of the study are to (1) evaluate the APSIM model in simulating crop yield, soil water, and N dynamics including N_2O emissions in the NCP; (2) apply the validated model to explore sustainable intensification options that have the potential to maintain grain yield with low environmental risk; (3) apply the validated model to optimize crop cultivar to provide the desirable genotypic traits information for agronomist to select suitable cultivars and for breeders to breed new cultivars.

2. Materials and methods

2.1. Study sites, soil, climate and crop data

This study focused on four agro-meteorological experiment stations in the NCP with contrasting geographical, climatic conditions, and complete field trial data. The four stations were Nanyang and Xinxiang stations in Henan Province, Taian station in Shandong Province and Luancheng station in Hebei Province (Fig. 1). The winter wheat-summer maize rotation is the representative cropping system in this region. The study region has monsoon climate with rainfall concentrated in summer. The wheat growth period is from mid-October to early June, and maize growth period is from mid-June to early October. During the wheat and maize growth period, weather conditions (radiation, temperature and precipitation) were different among the four stations (Table S1). Soil data for the four study stations were obtained from the second national soil survey data (National Soil Survey Office, 1994). The soil is classified as loam. The topsoil (0–20 cm) contained about 10.0–12.0 g kg^{-1} organic matter, 0.7–0.8 g kg^{-1} total N. The soil bulk density (BD), saturation water content (SAT), water content at drained upper limit (DUL) and lower limit of plant extractable water content (LL) for different soil layers in the 200 cm soil profile were presented in Table S2. The soil profile of the stations was representative of the dominant soil in the study area.

Daily meteorological data from 1981 to 2010 at each station including minimum and maximum temperature, sunshine hours and rainfall acquired from the Chinese Meteorological Administration (CMA). Daily solar radiation was calculated with daily sunshine hours according to the Angstrom equation (Prescott, 1940). Crop experimental data of

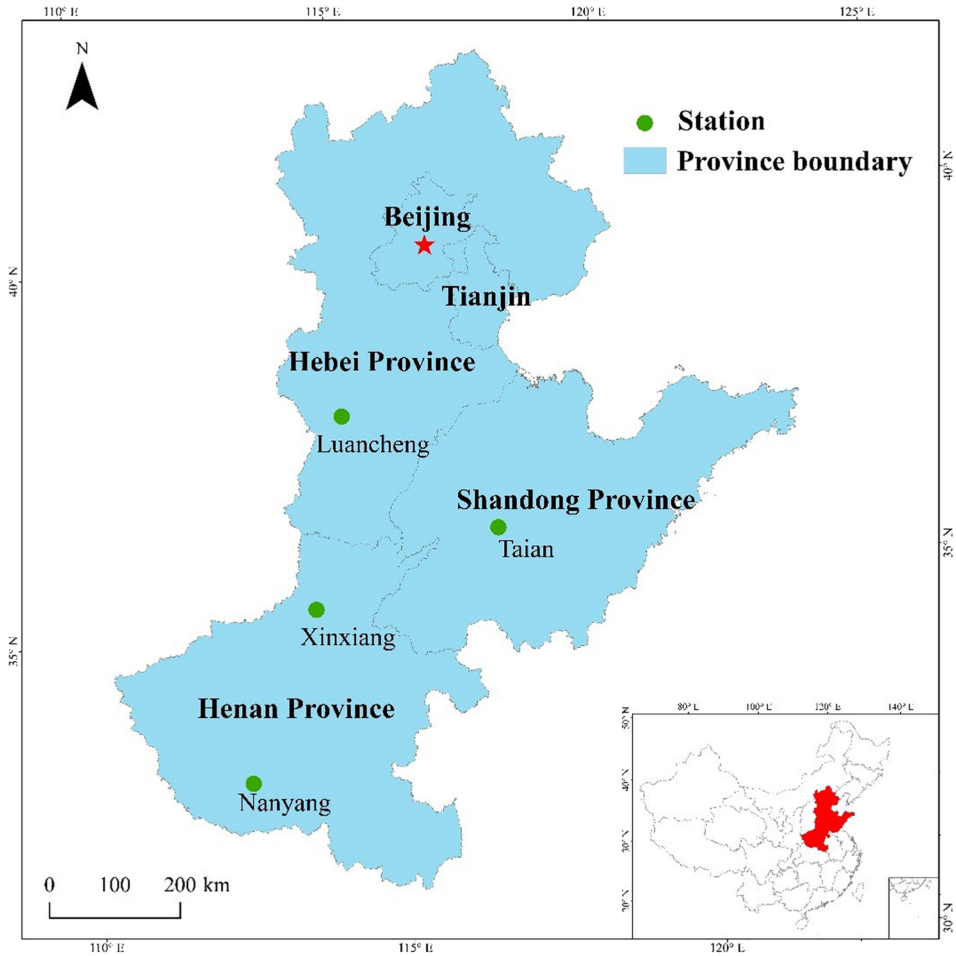

Fig. 1. Locations of the study stations.

the rotation at the four stations also obtained from the CMA, including cultivar type, crop key phenological stages, county average yield, yield and yield components and agronomic management practices. These field management practices at the four stations were nearly consistent with the local farmer's practices. Irrigation was only applied to wheat while maize was generally rain-fed in this region.

2.2. APSIM wheat-maize rotation model

The APSIM model is a component-driven mechanism model. It simulates crop growth and development, grain yield, water and nitrogen dynamics of soil in different planting patterns on a daily time step, responding to cultivar, management and climatic change (Keating et al., 2003; Holzworth et al., 2014). In recent years, it has been widely applied around the world to simulate the responses of both the productivity and environmental impacts of agricultural cropping systems in response to climate change and management practices (Holzworth et al., 2014; Gaydon et al., 2017; Hochman et al., 2017). It offers flexibility to specify management options and crop rotations. Many studies have reported that it is able to predict crop growth and development, soil water/nitrogen dynamics in the NCP (Chen et al., 2010; Xiao and Tao, 2014; Bai et al., 2016; Xiao et al., 2017) as long as the model is well calibrated and validated. Therefore, it can be applied to explore sustainable intensification options of the typical cropping system in the NCP for crop productivity improvement and climatic adaptation. The APSIM model version 7.8 was applied here to simulate grain yield and optimize sowing date, sowing density, irrigation input, nitrogen application rate and cultivar of the rotation in this region. The APSIM wheat-maize rotation model includes two sub-models: APSIM-wheat model and APSIM-maize model.

Parameters calibration and validation were performed before models were applied. Different statistical indices such as the coefficients of determination (R^2), D-index (Willmott, 1982) and the normalized root mean squared error (NRMSE) were used to check the agreement between observed and simulated values. The expressions were as follows:

(i) Coefficients of determination (R^2)

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(S_i-\bar{S}\right)\left(O_i-\bar{O}\right)\right]^2}{\sum_{i=1}^{n}\left(S_i-\bar{S}\right)^2\sum_{i=1}^{n}\left(O_i-\bar{O}\right)^2}$$

(ii) Normalized root mean squared error (NRMSE)

$$\mathrm{NRMSE} = \frac{\sqrt{\left[\sum_{i=1}^{n}(S_i-O_i)^2\right]/n}}{\bar{O}}$$

(iii) Index of agreement (D-index)

$$D = 1-\frac{\sum_{i=1}^{n}(S_i-O_i)^2}{\sum_{i=1}^{n}\left(|S_i-\bar{O}|+|O_i-\bar{O}|\right)^2}$$

where S_i and O_i were the simulated and observed values, $\bar{S}$ and $\bar{O}$ were the mean of simulated and observed values, respectively; n was the

sample number. The simulation was identified excellent if NRMSE was <10%, good if NRMSE was 10%–20%, fair if NRMSE was 20%–30%, and poor if NRMSE was >30%. According to the D-index, the closer the index value was to 1, the better the agreement between the two variables that were being compared and vice versa.

2.3. Optimizing sowing date and sowing density for the wheat-maize rotation

To derive the optimum sowing date for the wheat-maize rotation, the performance of the rotation was evaluated from 1981 to 2009 with maize sowing date changing from May 25th to June 25th at Nanyang and Luancheng, and from June 1st to June 30th at Xinxiang and Taian. Wheat was sown within 15 days after maize harvest in the rotation. Then the sensitivity of phenology and yield to sowing date was derived to determine the optimum sowing date for the wheat-maize rotation. Similarly, sowing density was set from 100 to 800 plants m^{-2} with an interval of 50 plants m^{-2} of wheat and 3 to 9 plants m^{-2} with an interval of 1 plant m^{-2} of maize to derive the optimal sowing density. Wheat and maize cultivars at each station chose the modern cultivars for the period of 2005–2009. Irrigation and N application rates for all were set in accordance with the common field management practices.

2.4. Optimizing irrigation and nitrogen application rate for the wheat-maize rotation

The performance of the wheat-maize rotation with APSIM was simulated under different irrigation treatments and nitrogen application rates from 1981 to 2009. In the study region, maize generally did not require irrigation because its growth period coincided with the summer rainy season. Thus, a continuous maize system was firstly simulated from 1981 to 2009 with the optimal sowing date and density in each station without irrigation. Then 11 levels of nitrogen rates ranging from 0 to 300 kg N ha^{-1} $year^{-1}$ with an interval of 30 kg N ha^{-1} $year^{-1}$ were applied. The simulated results were used to show the sensitivity of maize yield to different nitrogen application rates and then to determine the optimum N application rate for maize. According to the recommendation by experts and the long-term field trial data in the study region, N fertilizer was added equally at sowing and jointing stage. According to the yield and resource use efficiency, the optimal nitrogen application rate was determined and then would be used as a fixed N application rate for maize in the subsequent simulations of the rotation.

To investigate the optimal irrigation and nitrogen application rate for wheat in the wheat-maize rotation, the performance of the rotation was simulated from 1981 to 2009 with the optimal sowing date and sowing density at each station. In these simulations, six irrigation treatments were set for wheat: rainfed (W0), W1 (80 mm water at sowing), W2 (W1 + 80 mm water before overwintering), W3 (W2 + 80 mm water at jointing stage), W4 (W3 + 80 mm water at flowering stage) and W5 (W4 + 80 mm water at grain filling stage). For each irrigation treatment, there were 11 nitrogen application levels ranging from 0 to 300 kg N ha^{-1} $year^{-1}$ with an interval of 30 kg N ha^{-1} $year^{-1}$. According to the recommendation by experts and the long-term field trial data in this study area, 40% and 60% of the nitrogen fertilizer were applied as basal and jointing fertilizer, respectively. In the rotation simulations, maize was sown at the optimal N application rate that was determined by the previous step. According to the yield and resource use efficiency, the results were used to derive the optimal irrigation and nitrogen input for wheat.

The total grain yield, water or nitrogen uptake, water loss by drainage, N loss due to denitrification and nitrogen leaching below crop root zone and N_2O emissions were modelled to evaluate the rotation's productivity and environmental reaction in response to different levels of irrigation and nitrogen inputs. Based on the simulated results, the total yield, N loss by denitrification and N leaching, and water loss by drainage of the wheat-maize rotation under each irrigation and N treatment, were derived. Water use efficiency (WUE) of evapotranspiration (ET), WUE of irrigation, and nitrogen use efficiency (NUE) were calculated as:

$$\text{WUE of ET} = \text{yield}/\text{ET}$$

$$\text{WUE of irrigation} = \text{yield}/\text{amount of irrigation}$$

$$\text{NUE} = \text{yield}/\text{N application rate}$$

2.5. Optimizing crop cultivar for the wheat-maize rotation

In order to improve total yield and resource use efficiency of the wheat-maize rotation, it is an effective approach to breed new cultivars and select suitable cultivars for a target environment. APSIM was used to identify the performance of different sets of cultivars. Crop cultivar was defined as a set of cultivar-specific parameters related to growth development and grain formation of a crop with the given environmental condition in APSIM. By changing the cultivar parameters from given value ranges and optimizing them in response to environment condition, the optimal cultivar could be determined that showed the best yield performance under given environment condition (Tao et al., 2017). For wheat, there were five key cultivar parameters of the APSIM-wheat closely related to wheat development, biomass accumulation, and grain formation. The five parameters were sensitivity to vernalization (vern_sens), sensitivity to photoperiod (photop_sens), thermal time required from floral initiation to flowering (tt_floral_initiation), grains per gram stem (grains_per_gram_stem), and potential grain filling rate (potential_grain_filling_rate) (Table S3). Similarly, five key cultivar parameters were selected for maize, including thermal time required from emergence to end of juvenile (tt_emerg_to_endjuv), thermal time required from flowering to maturity (tt_flower_to_maturity), change in thermal time required to floral initiation per hour photoperiod increase (photoperiod_slope), maximum grain numbers per head (head_grain_no_max) and grain-filling rate (grain_gth_rate) (Table S4). The range of each parameter values for wheat and maize was determined by the reference values of wheat and maize in the APSIM. Five levels were set for each parameter, then for wheat and maize, respectively, 5^5 (3125) sets of cultivar parameters were generated by random combination of the five levels of the five parameters. The performance of these cultivars was assessed with the APSIM-wheat-maize at the four stations from 1981 to 2009 to identify desirable cultivar traits for wheat and maize, respectively. In all the simulations, sowing date and sowing density for wheat and maize were set to the optimal sowing date and sowing density determined above, respectively. Optimal irrigation and nitrogen application rates were applied to wheat, and the corresponding optimal nitrogen application rate was applied to maize according to the above.

2.6. Statistical analyses

The simulated data was subjected to analysis of variance tests (ANOVA) using SPSS 19.0. The Duncan's Multi-Range Test was applied to identify treatments for significant difference. In all the cases, differences were considered to be statistically significant if $P \le 0.05$.

3. Results

3.1. Calibration and validation of the APSIM wheat-maize model using field trial data

The APSIM wheat-maize model was calibrated and validated with the representative cultivar according to the field trial data during

2005–2009 at each station. The calibrated values of parameters for wheat and maize cultivars were shown in Table S5. The simulated anthesis date and maturity date of wheat and maize agreed reasonably well with the observed dates for both two crops at all of the four stations (Fig. S1). The differences between the simulated and observed phenological dates for either wheat or maize were <5 days on average. Additionally, simulated yields were also in good agreement with observed yields for both crops (Fig. S1). The relative errors of simulated yields were less 15% than observed yields. Generally, the results indicated that the calibrated APSIM model was reliable in simulating the growth and yield formation of wheat and maize in the study region.

3.2. Responses of the wheat-maize rotation to sowing date and sowing density

In the simulations, both anthesis and maturity dates of maize were postponed with the delay of maize sowing. With maize sowing delayed by one day, the length from sowing to anthesis decreased significantly ($P < 0.01$) by 0.06–0.13 days except Xinxiang, and the length from anthesis to maturity increased significantly ($P < 0.01$) by 0.33–0.55 days at all of the four the stations (Table S6). Additionally, the whole maize growth period lengthened significantly ($P < 0.01$) at the four stations. With the delay of maize sowing, wheat sowing date was postponed as

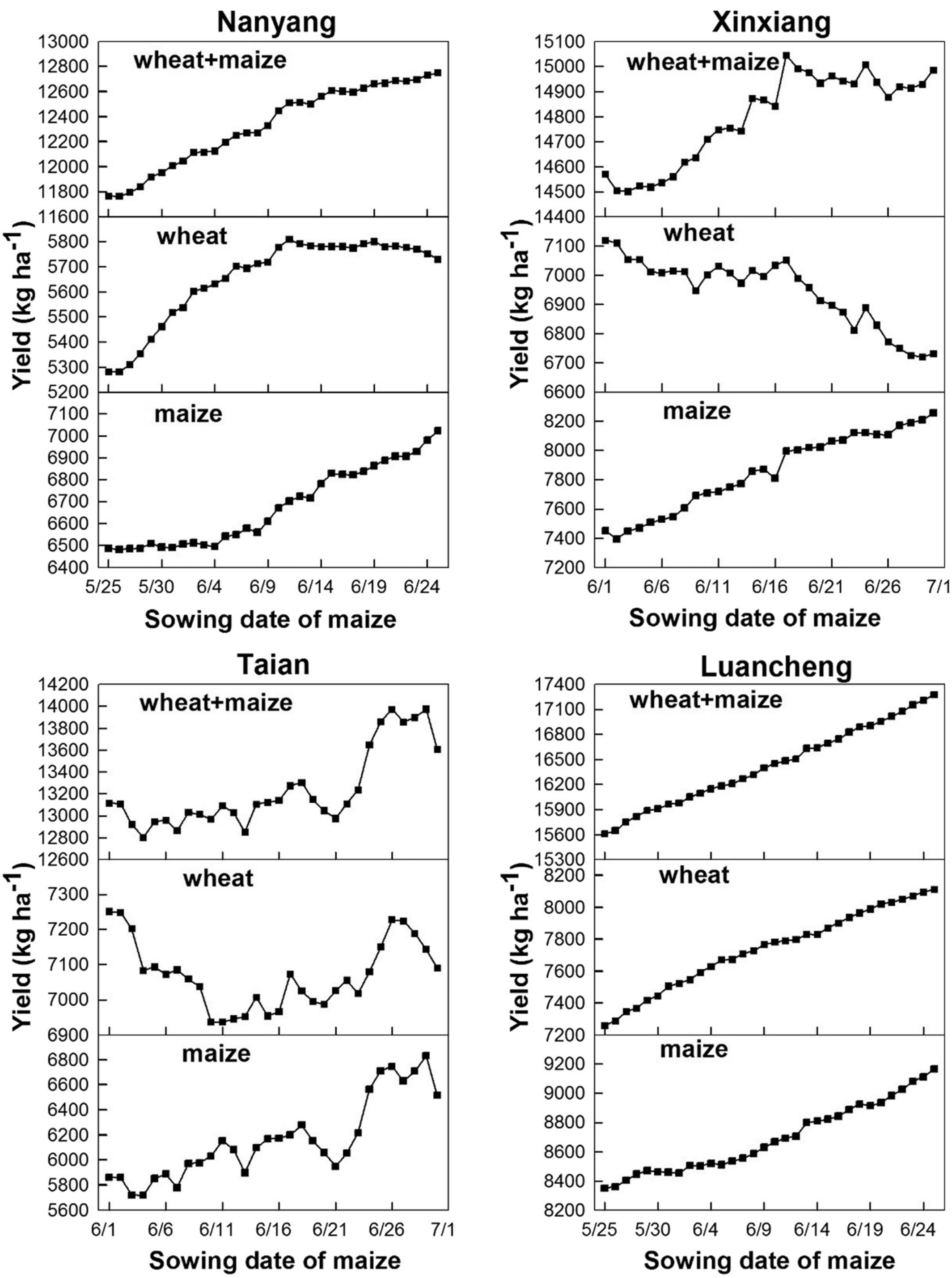

Fig. 2. Changes in yield of the wheat-maize rotation to sowing date of maize at the four stations (average of 29 years' simulated results from 1981 to 2009).

well. With maize sowing delayed by one day, the length of wheat from sowing to anthesis decreased significantly ($P < 0.01$) by 0.47–0.72 days at three stations, but did not change significantly at Nanyang. The length of wheat from anthesis to maturity decreased significantly ($P < 0.01$) by 0.02–0.29 days except Luancheng. Moreover, the whole growth period shortened significantly ($P < 0.01$) at all the four stations (Table S6).

Changes in yield of the wheat-maize rotation to sowing date of maize at the four stations were shown in Fig. 2. Wheat and maize yield of the wheat-maize rotation increased at Nanyang and Luancheng with delaying maize sowing date from May 25th to June 25th. Wheat yield reached a plateau when maize sowing was delayed after June 10th at Nanyang, while wheat yield increased steadily when maize sowing was delayed after June 14th at Luancheng. Maize yield kept increasing when sowing date was delayed after June 21st (Nanyang) and June 19th (Luancheng), respectively. The total yield of the rotation kept increasing at the two stations. At Taian station, maize yield increased when sowing date was delayed after June 21st. Moreover, wheat yield decreased first and increased when maize sowing was delayed after June 24th. The total yield of the wheat-maize rotation increased and kept a high level when maize sowing was delayed before June 30th. With delaying maize sowing from June 1st, maize yield increased at Xinxiang, while wheat yield decreased insignificantly when maize sowing was delayed after June 17th. The total yield of the wheat-maize rotation increased and kept a high level when maize sowing was delayed before June 24th. In conclusion, the optimal maize sowing date in the rotation should range from June 21st to June 25th at Nanyang, June 17th to June 24th at Xinxiang, June 24th to June 29th at Taian, and June 19th to June 25th at Luancheng, respectively. The corresponding sowing date of wheat was within 15 days after maize harvesting.

With the increase of sowing density, both two crop yield increased at all of the four stations. However, when sowing density of wheat and maize was higher than 550 plants m^{-2} and 8 plants m^{-2}, respectively, yield barely increased (Fig. 3). Therefore, the optimal sowing density for wheat and maize should be 550 plants m^{-2} and 8 plants m^{-2}, respectively.

3.3. Responses of the wheat-maize rotation to nitrogen application and irrigation

The maize yield, N content in grain, and WUE of ET all increased with N application rate, and reached a plateau when N application rate was 180 kg N ha^{-1} $year^{-1}$ (Fig. 4). At N application rate of 180 kg N ha^{-1} $year^{-1}$, the average maize yield, N content in grain, and WUE of ET in the study stations were 6632–7999 kg ha^{-1}, 109.4–128.5 kg ha^{-1}, and 17.0–25.6 kg mm^{-1}, respectively (Fig. 4a, c, f). The yield increase per unit increase in N application rate declined sharply with the N application rate increasing before 210 kg N ha^{-1} $year^{-1}$ (Fig. 4b). When N application rate was >180 kg N ha^{-1} $year^{-1}$, yield increase for per unit increase in N application rate was reduced to about 0.1–1.6 kg kg N^{-1}, which suggested that no further yield gain resulted from the increased N application rate. NUE reduced with the increased N input (Fig. 4e). NUE decreased from 148 to 22 kg kg N^{-1} when the N input increased from 30 to 300 kg N ha^{-1} $year^{-1}$. The drainage below maize root zone decreased with increasing of N application rate, and then maintained a lower stable level of 56–132 mm at N application rate of 180 kg N ha^{-1} $year^{-1}$ (Fig. 4d). The drainage was quite different among the four stations because of the different amount of precipitation during maize growth period. In addition, N loss by denitrification and N leaching increased with the increase of N application rate and increased sharply when N application rate was >90 kg N ha^{-1} $year^{-1}$ (Fig. 4g). Moreover, the N_2O emissions increased with the increase of N application rate, especially when N application rate was >120 kg N ha^{-1} $year^{-1}$ (Fig. 4h). Overall, to maximize yield and relieve environmental impact simultaneously in the study region, the optimal N application rate for maize was proposed to be 180 kg N ha^{-1} $year^{-1}$.

The simulated responses of wheat to different N application rates and irrigation treatments were shown in Fig. S2 when planted with maize in rotation. At all of the four stations, wheat yield was enhanced as N application rate and irrigation amount increased. Under the scenario of 400 mm (IR5) and 300 kg N ha^{-1} $year^{-1}$ for wheat growing

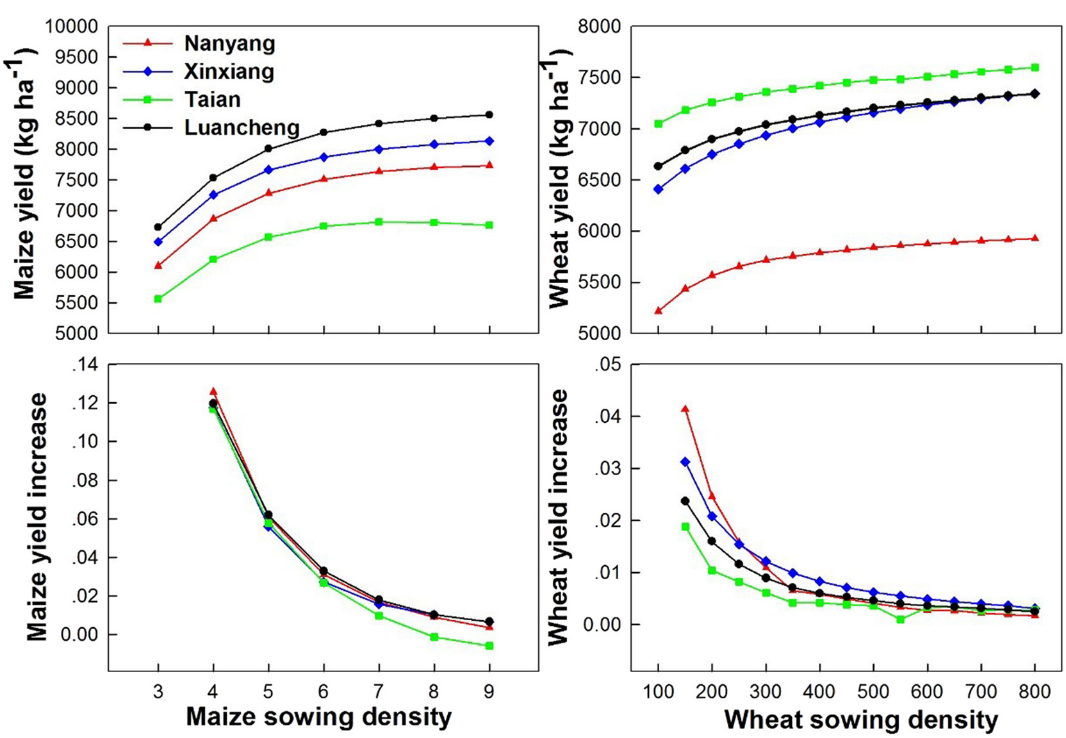

Fig. 3. Changes in yield of the wheat-maize rotation to sowing density at the four stations (average of 29 years' simulated results from 1981 to 2009).

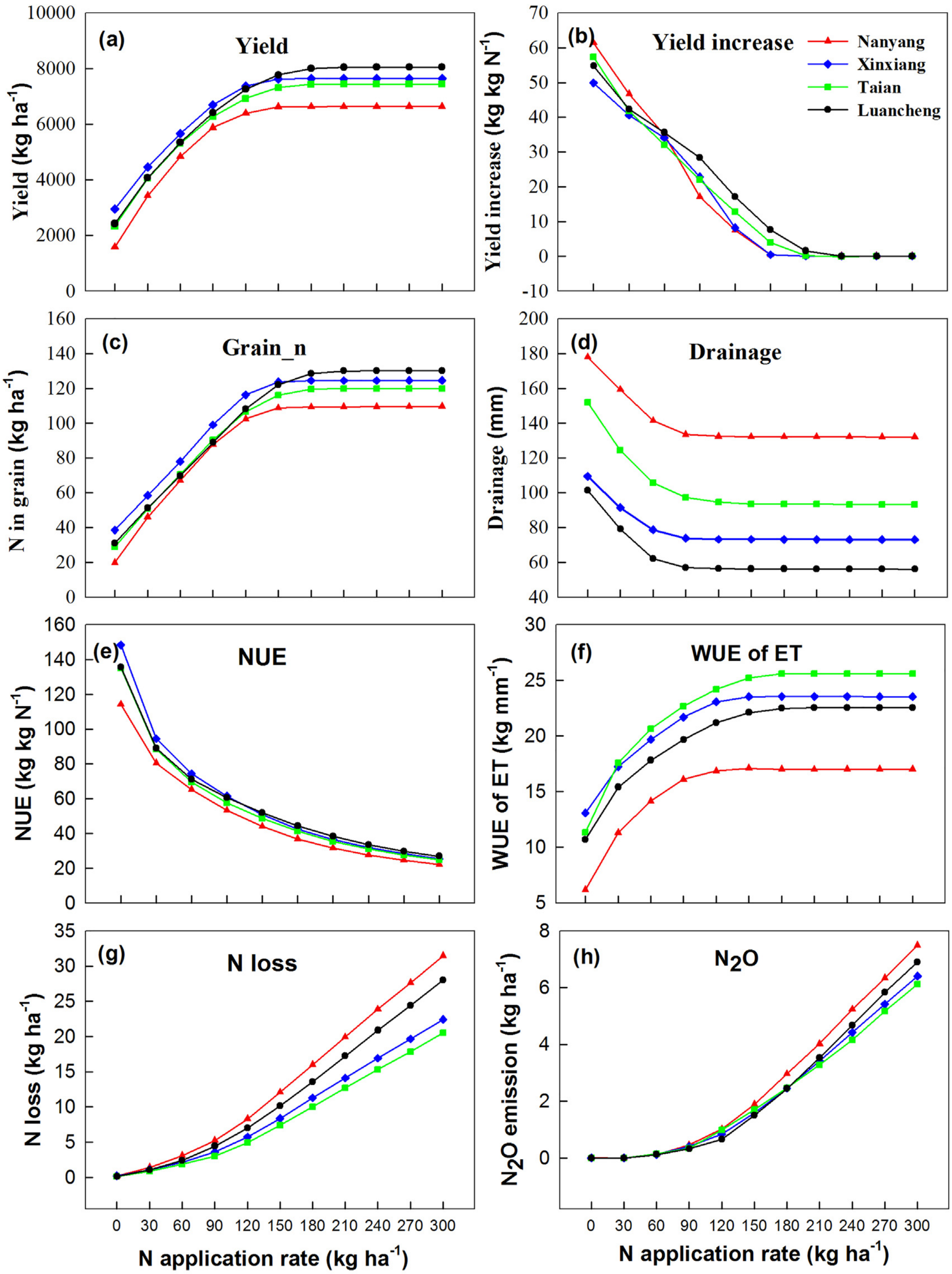

Fig. 4. Performance of continuous maize system in response to nitrogen application rates at the four stations (average of 29 years' simulated results from 1981 to 2009).

season, the maximum grain yield of wheat reached 9129, 10,331, 9996, and 10,584 kg ha^{-1} at Nanyang, Xinxiang, Taian, and Luancheng, respectively. On the other hand, 90% of the maximum grain yield has been achieved at 240 mm (IR3) with 180 kg N ha^{-1} $year^{-1}$, beyond which yield increase per unit increase in either irrigation or N rate dropped sharply. NUE and WUE declined with the increase of N rate and irrigation amount (Fig. S2). As nitrogen rate increased from 30 to 300 kg N ha^{-1} $year^{-1}$, the maximum NUE decreased from 154 to 30 kg kg N^{-1}, 149 to 34 kg kg N^{-1}, 138 to 33 kg kg N^{-1}, 166 to 35 kg kg N^{-1} at Nanyang, Xinxiang, Taian, and Luancheng, respectively. Likewise, the maximum WUE decreased from 60 to 23 kg mm^{-1}, 79 to 26 kg mm^{-1}, 79 to 25 kg mm^{-1}, and 81 to 26 kg mm^{-1}, respectively, as irrigation water amount increased from 80 to 400 mm. Moreover, there was no significant difference in NUE and WUE between 180 kg N ha^{-1} $year^{-1}$ with IR3 and other higher N application rates with higher irrigation treatments.

The simulated responses of the whole wheat-maize rotation to different levels of N application rate and irrigation for wheat were presented in Fig. 5. Under the five irrigation treatments, total grain yield of wheat-maize rotation increased with the increase of N input. The

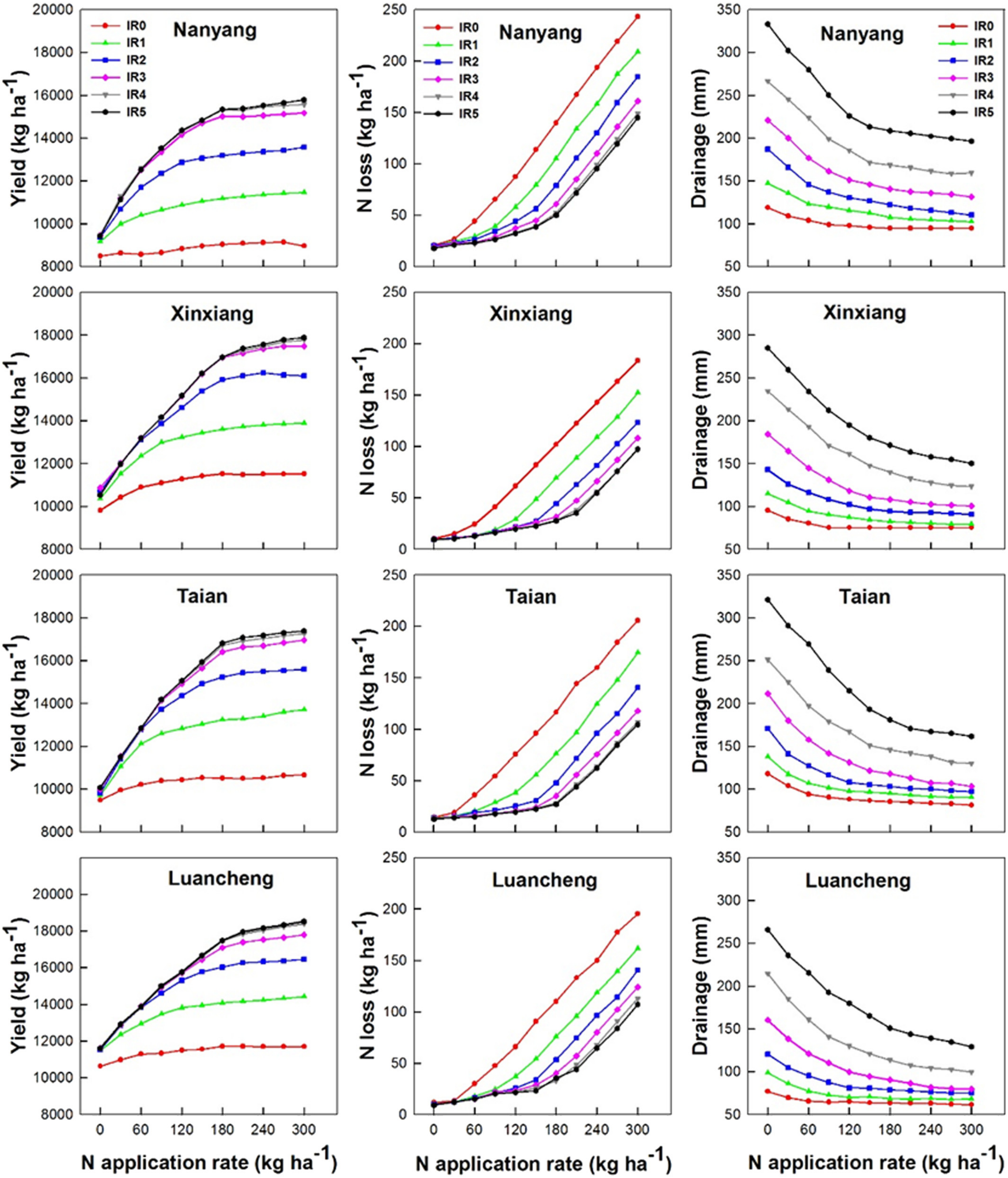

Fig. 5. Changes in yield, water and nitrogen loss of the wheat-maize rotation to irrigation water and nitrogen application rates at the four stations (average of 29 years' simulated results from 1981 to 2009).

total yield of wheat-maize rotation reached the maximum value at all stations with IR5 and 480 kg N ha^{-1} year^{-1} (180 kg N ha^{-1} year^{-1} for maize and 300 kg N ha^{-1} year^{-1} for wheat). The average maximum total yield (wheat plus maize) at Nanyang, Xinxiang, Taian and Luancheng were 15,780 kg ha^{-1}, 17,873 kg ha^{-1}, 17,392 kg ha^{-1} and 18,520 kg ha^{-1}, respectively. Moreover, 90% of the maximum yield achieved at 240 mm (IR3) with 150 kg N ha^{-1} year^{-1} for wheat. The increase of N application rate could reduce water loss from drainage of the

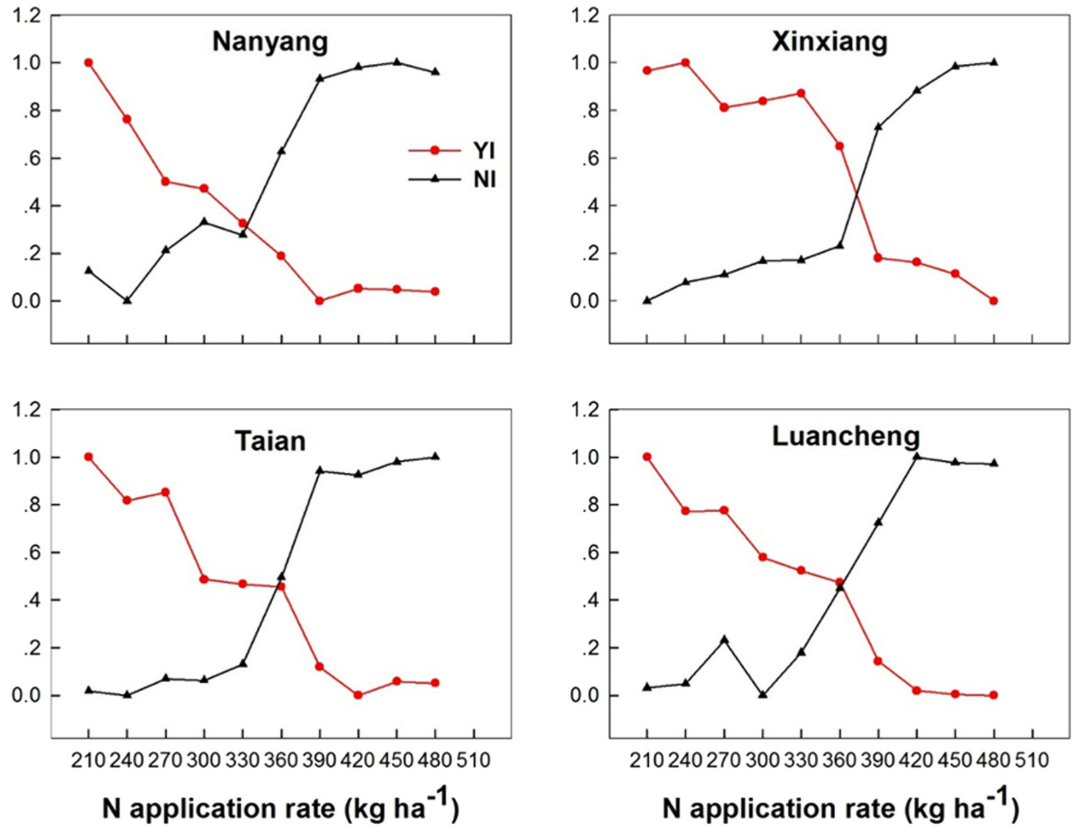

Fig. 6. Ecological suitable N application rate for the wheat-maize rotation. Yield increase is the amount of increased yield by one increased unit of N application. N loss and N_2O emissions increase is the amount of increased N loss and N_2O emissions by one increased unit of N application. YI, NI denotes yield increase, N loss and N_2O emissions increase after the normalization using the linear function method.

whole system, while aggravate N loss from denitrification and N leaching, especially when it was >360 kg N ha^{-1} year^{-1} (180 kg N ha^{-1} year^{-1} for maize and 180 kg N ha^{-1} year^{-1} for wheat). Higher irrigation treatments increased drainage and decreased N loss. IR3 could keep a good balance of drainage and N loss. With water supply of IR3 and N application rate of 180 kg N ha^{-1} year^{-1} during wheat season, the corresponding lower drainage and N loss were 90.5–140.7 mm and 31.6–60.9 kg ha^{-1}, respectively. More irrigation water could not reach significant changes in yield, drainage and N loss. N_2O emissions increased with the increase of N application rate and increased sharply when N application rate was >360 kg N ha^{-1} year^{-1} (180 kg N ha^{-1} year^{-1} for maize and 180 kg N ha^{-1} year^{-1} for wheat) at the four stations. N_2O emissions declined with irrigation increasing (Fig. S3). These results indicated that the N application and irrigation had positive interactions to promote uptake, thus reducing loss of water and N fertilizer. Considering the shortage of water resource and the overuse of fertilizer in the NCP, the optimal irrigation water amount for wheat should be 240 mm (IR3) to maximize yield and relieve environmental impact in the study region. In order to determine the optimal N application rate accurately, the increase of yield and the increase of N loss and N_2O emissions with IR3 irrigation treatment were both considered comprehensively (Fig. 6). As N application rate increased, yield increase per unit increase in N application rate decreased sharply, while N loss and N_2O emissions increase per unit increase in N application rate increased rapidly. The optimal N application rate was determined by the intersection of the two curves (YI & NI), which balanced yield and ecological benefit. If N application rate was higher than the optimal N application rate, N loss and N_2O emissions increased with N application rate. On the other hand, if N application rate was lower than the optimal amount, the negative environmental impact was relatively less while yield could not raise obviously. As demonstrated in Fig. 6, the optimal N application rate should be 330–360 kg N ha^{-1} year^{-1} at Nanyang and Taian, 360–390 kg N ha^{-1} year^{-1} at Xinxiang and Luancheng, respectively. Based on the above, 240 mm (IR3) and 150–210 kg N ha^{-1} should be the optimal irrigation water supply and N application rate for wheat in the study region. For the wheat-maize rotation, 330–390 kg N ha^{-1} year^{-1} (180 kg N ha^{-1} year^{-1} for maize and 150–210 kg N ha^{-1} year^{-1} for wheat) should be the optimal.

3.4. Sensitivity of crop yield to cultivar-specific parameters

For wheat, with the increase of vern_sens, grain yield increased at all the stations except Luancheng (Fig. S4), in which yield reached the maximum at vern_sens of 3. As photop_sens increased, yield increased first and reached the maximum at photop_sens of 5, 2, 3 and 4 at Nanyang, Xinxiang, Taian and Luancheng, respectively. With the increase of tt_floral_initiation, yield increased at all the stations except Nanyang. With the increase of grain_per_gram_stem, yield increased first and reached the maximum at grain_per_gram_stem of 36–44 at the four stations. At all of the four stations, yield was enhanced as the potential_grain_filling_rate increased. For maize, with the increase of tt_flower_to_maturity, head_grain_no_max and grain_gth_rate, yield increased at all the stations. In contrast, with the increase of tt_emerg_to_endjuv and photoperiod_slope, yield decreased at all the stations except Nanyang.

The high-yielding wheat cultivars were characterized with high potential_grain_filling_rate in the study area (Fig. 7). With the other cultivar-specific parameters fixed, the high-yielding cultivars were characterized with medium grain_per_gram_stem (i.e., GGS2 or GGS3). Moreover, with the increase of vern_sens, the high-yielding cultivars were characterized with high photoperiod sensitivity. The impact

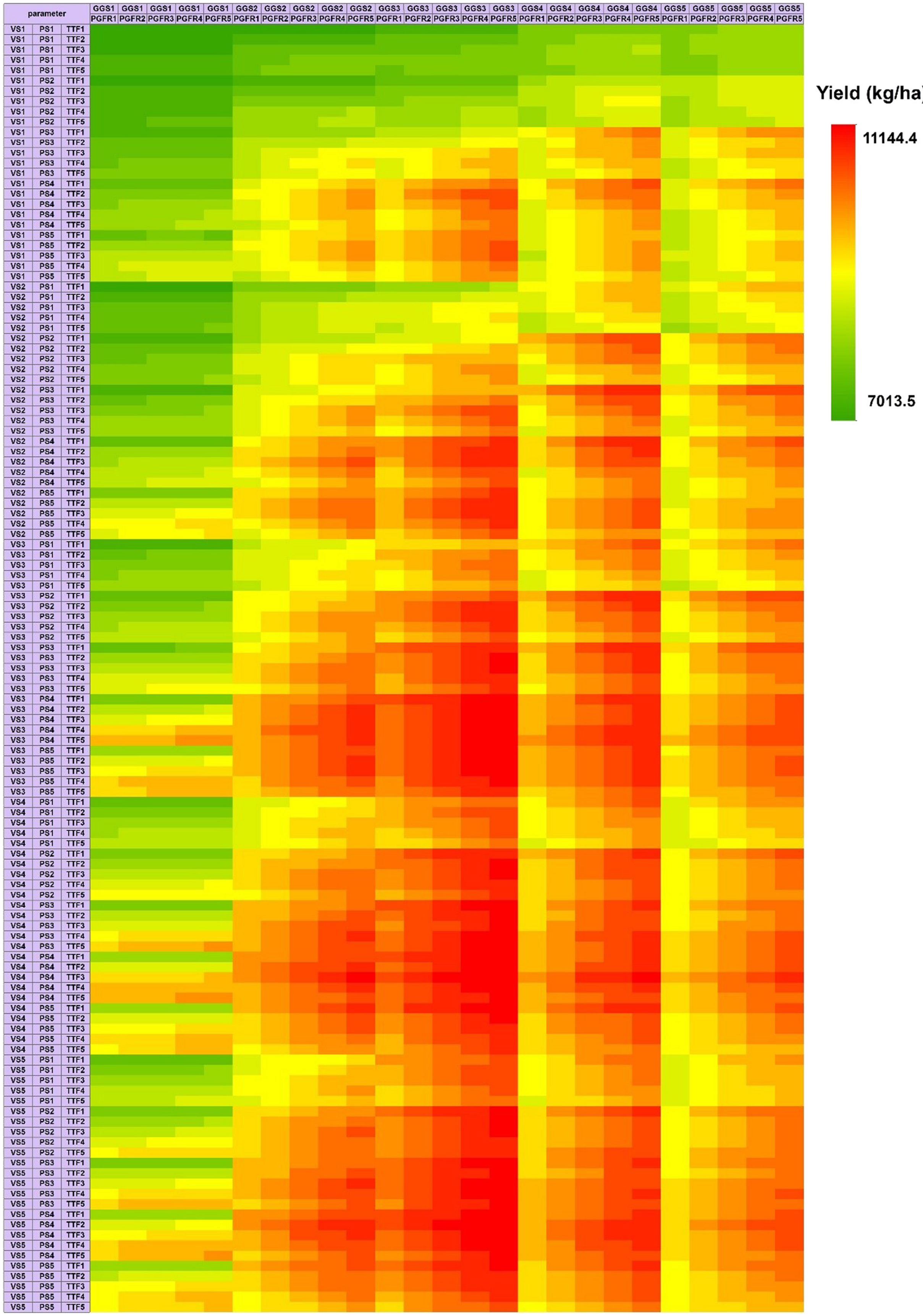

Fig. 7. Heatmap of the simulated wheat yield changes to cultivar-specific parameters.

of tt_floral_initiation on wheat grain yield was not regular. For maize in the study area, the high-yielding cultivars were characterized with high tt_flower_to_maturity, head_grain_no_max, and grain_gth_rate (Fig. S5). With other cultivar-specific parameters fixed, maize yield decreased with the increase of tt_emerg_to_endjuv and photoperiod_slope.

For the optimal five wheat cultivars, both vern_sens and photop_sens had obvious differences among different stations, but vern_sens and photop_sens were 3 and 4 at Luancheng (Table S7). Moreover, potential_grain_filling_rate was mainly 0.0036 at all of the four stations. At each station, the optimal five maize cultivars were characterized with low tt_emerg_to_endjuv, high tt_flower_to_maturity and head_grain_no_max (Table S8).

4. Discussion

The APSIM model has been widely applied in China to investigate the impacts of crop variety, climatic and agronomic management changes on crop growth and yield (Xiao and Tao, 2014; Bai and Tao, 2017). In the present study, it was used to assess productivity, resource use efficiency and environmental impact of wheat-maize rotation in the NCP by optimizing G × E × M interactions. Sowing date is a key factor for crop growth and yield because shifts of sowing date could affect climate during crop growth period and improper sowing date would exacerbate abiotic stresses on crops. Traditionally, winter wheat is sown in early October, harvested in early June of the following year, and then summer maize is sown, and harvested in late September in the NCP. In the study, the optimal sowing date for maize is suggested to be from June 17th to June 29th. But it is different at different stations because of the diversity of local climatic conditions and cultivar characteristics. In the recent years, the "Double Delay" technology (i.e., delay both the maize harvesting and wheat sowing) was proposed and applied for the wheat-maize rotation in the NCP to adapt to ongoing climate change (Tao et al., 2012; Wang et al., 2012), which is consistent with the results of the present study. With the delay of maize sowing, anthesis date actually advanced and the length from anthesis to maturity elongated because of increased temperature in our study. Moreover, the significantly increased length from anthesis to maturity contributed to yield gain due to longer duration for grain-filling (Muchow, 1990). Late sowing of maize resulted in postponing the sowing of winter wheat. The increase in temperature before over-wintering stage enabled late sowing of winter wheat, and late sowing reduced the risk of cold damage in early spring (Sun et al., 2007). While the length of growth period from anthesis to maturity and whole growth period significantly shortened despite of negative impacts of temperature increase, and the yield of wheat was still increasing in the study. The application of wheat cultivar with high grain filling rate contributed to the increased yield (Tao et al., 2012). Besides, popular application of farming machines and minimum tillage technology also shortened the time for field preparation from maize harvesting to wheat sowing, which promoted later harvesting of maize and later sowing of wheat (Wang et al., 2012). In fact, the shifts of sowing date, together with increasing adoption of cultivars with longer reproductive growth period, offset the negative climatic impacts and increased productivity (Tao et al., 2014).

The increase in sowing density has played an important role in improving grain yield (Ren et al., 2016). The yield was higher at relatively high sowing density due to a large grain number and good grain quality because crop could make full use of available light, water, and nitrogen resources. Our results showed that the optimal sowing density was 550 plants m^{-2} for wheat and 8 plants m^{-2} for maize in the NCP, which is supported by several previous studies (e.g. Yan et al., 2016). By contrast, the recommended sowing density was 650 plants m^{-2} for wheat in the rice-wheat rotation in southeast China (Bai et al., 2016). Therefore, optimal sowing density is environment-dependent and site-specific, which closely related to crop genotype, soil, climate, and agronomic management practices (Subedi and Ma, 2009). Therefore, the optimal sowing density should be determined reasonably with site-specific optimization of G × E × M interactions.

It is a hotspot to investigate how to increase grain yield and reduce negative environmental impact at the same time. In the study, we demonstrated an effective approach to find the solution for sustainable intensification through optimization of G × E × M interactions. Under the irrigation treatment IR3 (240 mm) for wheat, N application rate of 150–-210 kg N ha^{-1} $year^{-1}$ for wheat and 180 kg N ha^{-1} $year^{-1}$ for maize, the rotation could reach nearly maximum grain yield with relative high resource use efficiency and low N_2O emissions. Higher irrigation or nitrogen input would not get notable yield increase. This indicated that yield determinant should be other factors such as sowing date or density at high levels of water or nitrogen input. Our recommended optimal nitrogen application rates are supported by some previous experimental and modelling results in the study region (e.g. Huang et al., 2011; Zhao et al., 2015), which documented that the optimal N rate ranged from 150 to 180 kg N ha^{-1} $year^{-1}$ for a single crop. Our recommended optimal amounts were 40% less than the average irrigation of 400 mm and N fertilizer rates of 600 kg N ha^{-1} $year^{-1}$ for current agricultural practices in this area (Zhang et al., 2006; Zhong et al., 2006). The recommended agronomic management practices will have many benefits including increasing resource use efficiency, reducing N leaching and non-point pollution, mitigating GHG emissions, and recharging groundwater (Fang et al., 2013; Chen et al., 2014). In practice, it should be adjusted according to local conditions. The results confirm that it is possible to maintain crop productivity and reduce the negative impact on environment simultaneously by adopting the recommended agronomic management practices and increasing resource use efficiency.

In addition, cultivar selection and breeding has contributed greatly to improve agricultural system's ability to increase crop yield and adapt to variable climate for various crops in China (Zhou et al., 2007; Wang et al., 2012; Bai et al., 2016). Selecting suitable cultivars for a given environment and breeding climate resilient crop cultivars are the most efficient way to adapt to climate change (Tao and Zhang, 2010). Crop model has the potential to become an important means to support breeding new cultivars by identifying the ideotype for a target environment (Tao et al., 2017). In the study, the optimal cultivars that showed the best performance and adapted to the climate change were determined by shifting specific parameters about phenology and grain formation at each station. Temperature rise mainly occurred during the vegetative (pre-flowering) stage of wheat and maize (Liu et al., 2010; Tao et al., 2012). Therefore, new cultivars should not only stabilize the length of pre-flowering period against negative effect of warming, but also have longer grain-filling period and higher grain-filling rate to make full use of the ameliorated climate resources, which could increase crop yield greatly. In the NCP, more cultivars with longer growth period have been adopted (Sun et al., 2007; Wang et al., 2012). Our results showed that maize yield increased with decrease of thermal time from emergence to end of juvenile and increase of thermal time from flowering to maturity and grain-filling rate. This was also consistent with previous results that modern maize cultivars in Northeast China showing a significant increase in grain-filling rate (Chen et al., 2013). Wheat yield increased with increase of high potential grain filling rate. Flowering time of wheat was affected by vernalization and photoperiodism (Zhang et al., 2015). Our results showed that vern_sens was mainly less than or equal to 3 while photop_sens and tt_floral_initiation had obvious spatial heterogeneity for the high-yielding wheat cultivars at the four stations (Table S7), which mainly resulted from different environment conditions. The findings are helpful to provide the scientific basis for breeders to breed high-yielding cultivars and for agronomist to select suitable cultivars.

5. Conclusions

The APSIM was applied to develop sustainable intensification options for the typical wheat-maize cropping rotation in the NCP by

optimizing the G × E × M interactions. The optimal maize sowing date should be from June 17th to 29th and the corresponding wheat sowing date was within 15 days after maize harvesting in the NCP. This means that proper delay of sowing date could relieve the negative impact of climatic risk. The optimal sowing density was recommended to be 550 plants m^{-2} for wheat and 8 plants m^{-2} for maize to maximum grain yield. Irrigation of 240 mm (IR3) for wheat and nitrogen application rate of 330–390 kg N ha^{-1} $year^{-1}$ (150–210 kg N ha^{-1} $year^{-1}$ for wheat and 180 kg N ha^{-1} $year^{-1}$ for maize) were suggested to maintain higher productivity of the whole system with higher resource use efficiency and lower N_2O emissions. These were approximately 40% lower than those current level practiced by many local farmers, suggesting a large potential for optimal management practices to reduce environmental impact. The cultivars of wheat and maize with high grain filling rate are desirable. Our results are useful to improve productivity and eco-efficiency of the wheat-maize rotation simultaneously in the NCP. Moreover, this study demonstrates an effective approach to develop sustainable options through optimizing the G × E × M interactions for a target environment. The approaches adopted in this paper can be applied for other regions and typical agricultural systems to develop sustainable intensification options by adapting to the local conditions.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.11.126.

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